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Vibro-acoustic analysis and design optimization to improve comfort and sustainability of future passenger aircraft

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Abstract. The challenges of recent years lead to the development of greener aircraft. However, the concept of environmental sustainability cannot be declined on its own; economic sustainability is also required by increasing the services provided to the passenger, particularly comfort. This work aims to propose a design process for a new sustainable aircraft that takes into account both environmental sustainability, by reducing the aircraft's emissions with a new configuration, and economic sustainability, by introducing a series of solutions to increase comfort during flight, with particular attention to acoustic comfort, i.e. internal noise.

Introduction

Recent social developments have brought new demands to the design of commercial passenger aircraft. The environmental aspect has become paramount, and the new aircraft of the future must be low emission. At present, the most promising technologies, in addition to aircraft optimization, see a complete overhaul of the current configuration: a cylindrical fuselage with lifting wings and a combustion-based propulsion system. Major research involves completely different configurations (blended wing body aircraft, etc.) and new propulsion systems (hydrogen, biofuel). However, these technologies, although certainly with very low emissions, lead to an increase in the aircraft's production and operating costs. An increase that has repercussions on airlines and thus on ticket prices for users. A further addition to the sustainability paradigm becomes necessary in order to make these new technologies available to all: which cannot only be environmental, but also economic. This aspect can be developed either by trying to reduce the cost of these technologies or by offering a better flight experience to the passenger, e.g., by increasing the comfort of the journey. In this paper we focus on the second aspect, which in addition to containing the seemingly inevitable increase in ticket costs due to the change in technology,[1,2] leads the aircraft to suffer less competition from other means of transport, such as high-speed trains or road transport, particularly for regional or short-haul routes.

The main location of the flight, and therefore what we will be dealing with, is the passenger cabin. Comfort during a flight depends on several factors and can be divided according to [1] into visual, interaction, postural, acoustic, or thermal comfort. Each of these depends on several factors, the former on ergonomics, interior design and lighting, acoustic comfort by the noise level and its spectrum, thermal comfort, often coupled with acoustic, is a function of cabin temperature and its variation. In this work, the focus has been on acoustic comfort, and thus on interior noise. In fact, several improvements can still be achieved in this field, for example by applying new generation absorbent materials. Furthermore, the probable innovation in the aviation sector will lead to a total

[1] https://www.iea.org/reports/the-future-of-hydrogen
[2] https://www.iea.org/data-and-statistics/charts/fossil-jet-kerosene-market-price-compared-with-hefa-aviation-biofuel-production-cost-2019-2020

change in the aircraft, and acoustic studies will be necessary to understand the new acoustic behavior of the aircraft.

The internal noise problem in aircraft can be broken down into three issues:

- how to evaluate this problem, therefore which parameters must be used to quantify the noise, understood not simply with sound, that is an acoustic pressure, but as a disturbance for the passengers;
- how to calculate numerically or experimentally, if possible, this noise inside a complex structure such as that of an aircraft;
- how to reduce, once quantified, this noise, without significantly changing the performance of the aircraft, i.e., by increasing its weight.

In design phases comfort evaluation can follow two different paths to measure it [2]. A human model-based measurement considers the human as a model, which generally has some maximum, minimum and average parameters. These can be obtained from physical and physiological laws (e.g., the size of a passenger for ergonomics or the maximum loud noise) or from statistical survey proposed to the users (the passengers, the crew, and the pilots). The advantage of this approach is the simplicity, and the fact that it can be applied at any step of the design process. However, these parameters do not consider subjective measurements and are unable to capture user's perception in terms of emotions. In order to improve comfort, it is important to have a user centered design process. This is possible through cabin or interior mock-up, where the user experience is evaluated with questionnaires surveys using psychometric scales. In the preliminary design phases, the main issue is the availability of large and detailed mock-ups. Nonetheless, new technologies as virtual reality and augmented reality can create virtual mock-ups in a more flexible and cheaper way, allowing to switch and submit to the user several design concepts and possible improvements [3]. In noise evaluation the human model-based measures are the standard practice, and they are used in this work. Usually, a noise level above 85 dB must be avoided for health reasons (the level is lowered for long exposure, as in residential area), we measure the noise in the possible positions of passengers during flight and we apply filters to acoustic pressure to take in account the human's ear sensibility (the A, B, C and D filters). A concept for human centered design process for noise evaluation is proposed in [4, 5].

The second open question can be simplified: studies of an experimental nature on complete or partial aircraft are almost impossible in the preliminary phases of the design, while in the more advanced phases they remain very expensive and complex, limiting the flexibility of the design process. Therefore, they are recommended only in the last stages. Numerical analyses are very useful; however, it is necessary to clearly define the methods used and their accuracy linked to the computational cost. Traditionally, the noise problem in the frequency domain is studied through Finite Element Method (FEM) and Boundary Element Method (BEM) when dealing with large acoustic cavities, for low frequency. High frequency problems are solved through Statistical Energy Analysis (SEA) methods. Middle frequencies are an open issue and hybrid models can be exploited. In this work we focus on low frequency noise, which is difficult to absorb or to stop with conventional material and acoustic solution. The method to study the problem and develop solutions is FEM. Nevertheless, in order to increase the accuracy of the problem and decrease the computational effort, the numerical analyses are carried inside the Carrera's Unified Formulation (CUF) framework, which exploits a class of powerful shell and beam theories [6].

The reduction of perceived noise can follow different paths: active and passive solutions have been proposed and studied for the noise aircraft problem [7, 8]. A very promising technology is Acoustic Metamaterials (AMMs). These materials provide optimal sound absorption properties in the chosen frequency ranges. They are composed of a host material, such as foam, and inclusions of another material. By playing with the size of these inclusions and their position, the acoustic and mechanical properties of the AMM are modified. This can be studied at a preliminary level in the CUF frame and then applied inside the passenger cabin and the aircraft itself, for example in the lining panel separating the fuselage and cabin.

In conclusion, alongside the more traditional elements in the design of a commercial aircraft, such as safety and performance, there is also sustainability, which to be truly sustainable must include both environmental sustainability, due to concerns about global warming and increased pollution in certain areas, and economic sustainability, in order to ensure the survival of the aviation market. If an increase in ticket prices might be inevitable by changing the propulsion system completely, i.e., switching to hydrogen or biofuel, it is possible to offer the user a better service, increasing comfort during the flight. The first step, proposed in this work, focuses on acoustic comfort and thus the reduction of noise in the passenger cabin.

CUF integration

In order to be used in the vibro-acoustic field, the CUF requires some integration, both in the formulation itself and in the procedure part within the software in which the formulation is developed, MUL2. In the CUF framework the fluid-structure coupling is integrated within the fluid matrices in terms of fundamental nuclei [6]. The major changes are summarized below:

- vibro-acoustic validation [9];
- acoustic boundary conditions and source [10];
- new adaptive finite elements [11], wh1ich allow to study complex geometries and variable thickness plates. Moreover, this concept lays the foundation for the development of non-homogeneous interfaces.

These integrations give the possibility to study vibro-acoustic problems in simple and complex structures in order to develop solutions at a preliminary level for noise reduction or to understand the spread of noise and vibration in advanced multi-layer structures. Other developments are being studied, regarding the concept of Adaptive Finite Element based on [12, 13].

Noise reduction solutions: AMM

Low frequencies, although attenuated by the human ear, are complex to absorb. This can be explained by the following simple relationship, valid for a plate, where the Transmission Loss TL is proportional to the thickness d and density ρ of the plate and the angular frequency $\omega = 2\pi f$ (or to the frequency f) of the acoustic signal:

$$TL \propto d \cdot \rho \cdot \omega \tag{1}$$

Therefore, for low-frequency noise, in order to have a high TL, it is necessary to use materials with high density or thick plates. Both cases result in an increase in system weight, which in the aeronautical field is to be avoided, as it is linked to an increase in fuel consumption.

Unconventional materials, such as AMMs, can achieve high TL values even in low frequency ranges due to their properties [14]. In this work, two types of AMMs are studied:

- a first one developed within the CUF and made by melamine foam with cylindrical inclusions [15], Fig. 1;
- a second produced using additive printing techniques (Fused Deposition Modeling FDM) and numerically studied using a Layer Wise (LW) approach [16], Fig. 2.

The AMMs studied exhibit very different behaviors, with the former reaching high *TL* values below 300 Hz, while the latter strongly attenuates noise around 1000 Hz, thus now in the mid-frequency range. In general, an attempt is made with these materials not to increase the weight of the system compared to conventional solutions applied in the cabin lining panel.

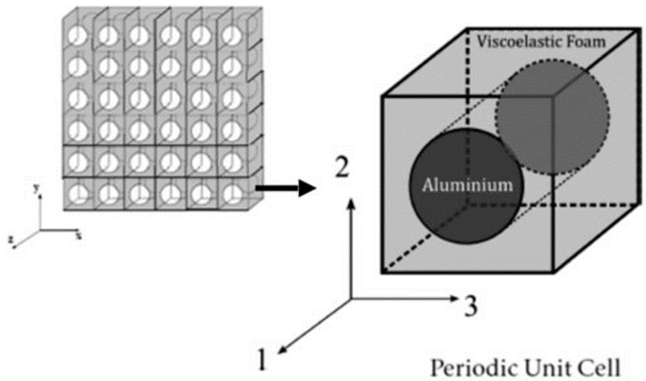

Figure 1: the first AMM used to reduce noise and developed in [15]

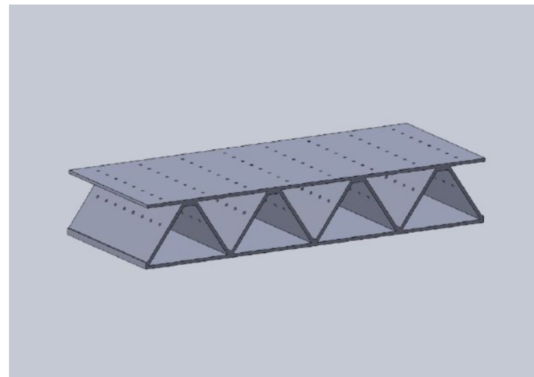

Figure 2: the second AMM produced with additively produced (FDM) in [16].

The aircraft passenger cabin

The passenger cabin is the center of the comfort problem, being the main, if not the only, place the user frequents. This is why, before moving on to its vibro-acoustic study, it is necessary to give a brief description from an acoustic point of view, within the fuselage, which holds the cabin. As described in Fig. 3 the cabin-fuselage system is composed by:

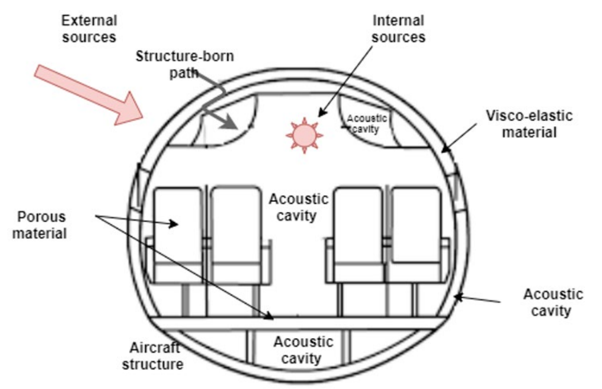

Figure 3: The sketch of a section of the fuselage and passenger cabin from an acoustic point of view. The different vibro-acoustic components and phenomena are underlined in order to show the complexity of the problem.

- the primary structure includes the aircraft skeleton, so the stringers, the frames and panels of the fuselage, the passenger and cargo decks supports and their panels on which the floor is placed, the bulkhead and wing box. Moreover windows frames, first glass pane and reinforcements are included in this subsystem;
- the secondary structure includes seats with their supports, lining, ceiling and dado panels of the cabin, overhead luggage compartment and luggage compartment in the cargo hold;
- cabin interiors, as the floor carpet, the galleys and the toilets;
- several subsystems, as the air conditioning and pressurization system, the electrical system, the thermal insulation system, etc;
- passengers, crew and luggage;
- acoustic cavities, in the fuselage there are several cavities filled by air, such as the passenger cabin, the cargo hold, the gap between the lining panel and the fuselage, the small air gap in the windows.

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From an acoustic point of view, we must understand the contribution of each subsystem. Nevertheless, the high complexity of the system requires some degree of simplification, and some components or subsystems are neglected or simplified.

The passenger cabin FEM model generation

The above description shows the need to simplify the vibro-acoustics model of the fuselage and cabin, eliminating those subsystems that do not counteract the N&V point of view (at least apparently) and simplifying others, the description of which would be too complex, or because there is no detailed information about them. Finally, possible external and internal sources must also be considered. Again, in order to avoid over-complicating the model, it is necessary to include them as external sources, i.e., structural or acoustic loads. Therefore, the major limitations in generating the FEM model are:

- lack of adequate information, either because this is not available or because the systems in question have not yet been fully define in the design process;
- computational cost, in dynamic problems, increasing the maximum frequency of the problem is inversely proportional to the size of the elements, so increasing the maximum frequency increases the number of DoF;
- accuracy of analysis, some types of structures require advanced approaches and in general special attention must be paid to the size (1D, 2D or 3D) of the elements in the various components (for example, the lining panels require a 3D formulation for the core or a 2D-LW approach, the stringers, and frames shell elements in order to avoid a numerical increase in the stiffness).

Sensitivity study

Once the FEM model has been constructed, a sensitivity study can be carried out to assess how the internal noise varies by varying the configuration of the structure, inserting new acoustic solutions, such as the AMMs proposed here, and varying the acoustic sources.

The results partially reported in [17, 18] show the potential of AMMs with an important noise reduction. Furthermore, this reduction was demonstrated for different fuselage models. As an example, the sound pressure maps in the passenger cabin applying the AMM in [15] are shown in Fig. 4. The results are calculated at ear height of seated passengers. However, the computational cost remains a significant constraint in this type of analysis. Obviously, for the study of new configurations such as in [17] it is necessary to consider the extended concept of environmental and economic sustainability, as reported for a windowless configuration in [19]. Alongside a reduction in fuel consumption, the acoustic behavior did not change and therefore additional acoustic solutions were required, i.e., AMMs.

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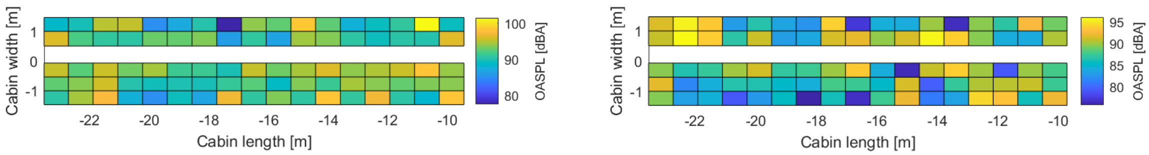

Figure 4: The Overall Pressure Level (OASPL) [dBA] maps on the positions of the seated passenger's heads in fuselage under an external complex pressure field [17]. The cabin of the model is composed by eighteen rows with five seats each one (from the bow on the right to the aft on the left). There is an increase in OASPL near the propeller position between row 2 and 5. (a) Lining panel core in Nomex in traditional fuselage. (b) Lining panel core in AMM in traditional fuselage.

Conclusions

In conclusion, the increase of comfort, including acoustic comfort, for the passenger during the flight can lead to an increased competitiveness of air transport with respect to other means of transport. Therefore, it is necessary to propose new solutions for noise reduction and tools to characterize noise development in the cabin. Therefore, it is necessary not only to study new solutions for noise reduction, such as AMMs, but to define a design process for the study of noise and vibration. This vibro-acoustic analysis must take into account the new innovative materials, both used in aeronautics and designed to reduce noise, and therefore use advanced approaches such as those available thanks to CUF (as Layer Wise approaches). In fact, this formulation makes it possible to save significant degrees of freedom and thus raise the maximum frequency of the problem or include new elements, without having a decrease in accuracy. In addition, the lower computational cost of analysis can lead to easier integration of aircraft acoustic optimization (also including vibro, aero and thermo-acoustics) in a multi-disciplinary optimization (MDO) process. Furthermore, in the future new tools for assessing the impact of noise on the comfort of passengers must be developed, placing the user at the center of the design process.

References

[1] D.P. Restuputri, K. Purnamasari, N. Afni, S. Legtria, E. Shoffiah, M. Septia, and I. Masudin. Evaluation of aircraft cabin comfort: Contributing factors, dissatisfaction indicators, and degrees of influence. AIP Conference Proceedings, 2453(1):020047, 2022. https://doi.org/10.1063/5.0094297

[2] S Bagassi, F Lucchi, F De Crescenzio, and S. Piastra. Design for comfort: aircraft interiors design assessment through a human centered response model approach. In 31st ICAS 2018 Proceedings, 2018.

[3] F. De Crescenzio, S. Bagassi, and F. Starita. Preliminary user centred evaluation of regional aircraft cabin interiors in virtual reality. Scientific Reports, 11, 05 2021. https://doi.org/10.1038/s41598-021-89098-3

[4] S. Santhosh, M.C Moruzzi, F. De Crescenzio, and S. Bagassi. Spatial sound system to aid interactivity in a human centred design evaluation of an aircraft cabin environment. In XXVI AIDAA Congress Proceedings, 2021.

[5] S. Santhosh, M.C. Moruzzi, F. De Crescenzio, and S. Bagassi. Auralization of noise in a virtual reality aircraft cabin for passenger well being using human centred approach. In 33rd ICAS 2022 Proceedings, 2022.

[6] E. Carrera, M. Cinefra, M. Petrolo, and E. Zappino. Finite element analysis of structures through unified formulation. Wiley, 2014. https://doi.org/10.1002/9781118536643

[7] A. Filippone. Aircraft Noise: Noise Sources, pp. 470-532. Cambridge Aerospace Series. Cambridge University Press, 2012. https://doi.org/10.1017/CBO9781139161893.019

[8] L.L. Beranek. The noisy dawn of the jet age. Sound and Vibration, 41:94-99, 2007.

[9] M. Cinefra, M.C. Moruzzi, S. Bagassi, E. Zappino, and E. Carrera. Vibro-acoustic analysis of composite plate-cavity systems via cuf finite elements. Composite Structures, 259:113428, 2021. https://doi.org/10.1016/j.compstruct.2020.113428

[10] M.C. Moruzzi, M. Cinefra, and S. Bagassi. Analysis of an acoustic monopole source in a closed cavity via cuf finite elements. Aerotecnica Missili & Spazio, Aug 2022. https://doi.org/10.1007/s42496-022-00129-2

[11] M.C. Moruzzi, M Cinefra, S Bagassi, and E. Zappino. Vibro-acoustic analysis of multi-layer cylindrical shell-cavity systems via cuf finite elements. In 33rd ICAS 2022 Proceedings, 2022. https://doi.org/10.1016/j.compstruct.2020.113428

[12] M. Cinefra. Non-conventional 1d and 2d finite elements based on cuf for the analysis of non-orthogonal geometries. European Journal of Mechanics/A Solids, 88:104273, 2021. https://doi.org/10.1016/j.euromechsol.2021.104273

[13] M. Cinefra. Formulation of 3d finite elements using curvilinear coordinates. Mechanics of Advanced Materials Structures, pages 1-10, 2020. https://doi.org/10.1080/15376494.2020.1799122

[14] S. Chen, Y. Fan, Q. Fu, H. Wu, Y. Jin, J. Zheng, and F. Zhang. A review of tunable acoustic metamaterials. Applied Sciences, 8(9), 2018. https://doi.org/10.3390/app8091480

[15] M. Cinefra, G. D'Amico, AG. De Miguel, M. Filippi, A. Pagani, and E. Carrera. Efficient numerical evaluation of transmission loss in homogenized acoustic metamaterials for aeronautical application. Applied Acoustics, 164:107253, 2020. https://doi.org/10.1016/j.apacoust.2020.107253

[16] M.C. Moruzzi, S. Bagassi, M. Cinefra, M. Corsi, and M. Rossi. Design of additively manufactured metamaterial for cabin noise and vibrations reduction. In XXVI AIDAA Congress Proceedings, 2021.

[17] M.C. Moruzzi, M. Cinefra, and S. Bagassi. Vibroacoustic analysis of an innovative windowless cabin with metamaterial trim panels in regional turboprops. Mechanics of Advanced Materials and Structures, 28:1-13, 2019. https://doi.org/10.1080/15376494.2019.1682729

[18] M.C. Moruzzi, M. Cinefra, S. Bagassi, and E. Carrera. Attenuation of noise in the cabin of a regional aircraft by metamaterial trim panels. In 32nd ICAS 20020 Proceedings, 2021.

[19] MC. Moruzzi and S. Bagassi. Preliminary design of a short-medium range windowless aircraft. International Journal on Interactive Design and Manufacturing (IJIDeM), 14(3):823-832, Sep 2020. https://doi.org/10.1007/s12008-020-00676-7